# EXTERNAL FULL-TIME VACUUM LYSIMETER DRAINAGE SYSTEM

S. R. Evett, B. B. Ruthardt, K. S. Copeland

**ABSTRACT.** *Low-cost weighing lysimeters have been demonstrated with accuracies better than 0.1 mm. However, these low-cost lysimeters lack full-time vacuum drainage systems; and they lack access to the lysimeter tank for installation and maintenance of a vacuum system. Without frequent manual drainage, such lysimeters can become waterlogged. We designed, implemented, and characterized the performance of an automatic vacuum drainage system that can be added to a low-cost lysimeter externally (provided that drainage filters were installed in the lysimeter and plumbed to the outside). The system consists of a buried vertical cylindrical vacuum chamber, inside of which a drainage collection tank is suspended from a load cell. A small enclosure containing a vacuum pump, vacuum sensor, and ports for accessing the drainage chamber is situated above the vacuum chamber and level with the field surface. Disturbance of wind patterns and energy and water balances in the field is minimized by the buried system. At 0.0013 mm, accuracy of drainage measurement was nearly two orders of magnitude better than that of the lysimeter mass measurement, ensuring that the continuous drainage measurement may be included in the mass balance determination of evapotranspiration (ET) without diminishing the accuracy of ET values. The system design, installation, and testing are described.*

**Keywords.** *Lysimeter, Vacuum drainage, Evapotranspiration, Crop water use.*

Low-cost weighing lysimeters have allowed measurement of crop water use (evapotranspiration or ET) in situations that otherwise would not be conducive to direct ET measurements by weighing lysimetry due to remoteness or expense (Schneider et al., 1996, 1998; Piccinni et al., 2002). Low-cost weighing lysimeters are typically designed with an outer enclosure that is only slightly larger than the soil tank. While such lysimeters are usually outfitted with drainage filters at the bottom of the soil column, these are usually plumbed to the top of the soil column where they may be manually connected to a vacuum pump for drainage. Access to the lysimeter for such periodic drainage may be constrained by field condition, the crop, and the desire to not disturb the area near the lysimeter. While space could be provided at the bottom of the outer enclosure for installation of a vacuum system, drainage holding tank, etc., this adds cost to the installation. Providing access to such a vacuum system for maintenance requires addition of an above-ground hatch and ladder, further increasing the total lysimeter cost.

However, vacuum drainage is required in order to maintain a water content profile that is reasonably similar to that in the adjacent field, so that luxury consumption of water by the lysimeter crop does not occur, which would result in over estimation of ET. This is particularly true for shallower lysimeters (Tanner, 1967; van Bavel, 1961). Pruitt and Angus (1960) described a vacuum drainage system for the 6.1-m diameter lysimeter at Davis, California. In that design, drainage was collected in tanks that were suspended from the lysimeter weighing mechanism so that no change in lysimeter mass was registered during drainage. A similar concept is used in the large weighing lysimeters at Bushland, Texas, except that the drainage tanks are suspended from the bottom of the lysimeter tank using load cells so that the drainage amount over short time periods may be recorded by datalogger. Other effects of differences in soil water content profile between lysimeter and field are differences in soil thermal conductivities and temperatures, possibly affecting root growth and water uptake, and differences in soil aeration, which also affects root water uptake.

In 1995, a low-cost weighing lysimeter was installed at the USDA-ARS Conservation and Production Research Laboratory at Bushland, Texas for reference grass ET measurements (Schneider et al., 1998). This lysimeter was successfully used, largely because the combination of a shallow-rooted crop (grass) and the 2.4-m depth of the soil column allowed drainage to accumulate at the bottom of the lysimeter without becoming accessible to the crop. If the accumulated drainage water had been available to the crop, it could have resulted in luxury consumption of water with resulting bias in the ET data. For a deeper rooted crop the possibility of luxury consumption would be more likely. Access to the lysimeter for manual drainage was not always possible when precipitation and irrigation left the surrounding soil soft; and, timing of other field work sometimes delayed manual drainage. In this article we describe the design, installation, and test of a full-time, external, hidden automatic drainage system for this lysimeter.

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The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

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## Design Criteria and Decisions

A reasonably long period before the drainage tank became full was desired. Experience with the vacuum drainage systems installed on the large weighing lysimeters at Bushland led us to conclude that a drainage storage tank of 110-L capacity would suffice over most growing seasons. Therefore an 1112-N (250-lb) load cell was selected, and drainage storage tank capacity was designed at 110 L. The mass measurement precision of the drainage system was required to be at least an order of magnitude better than that of the lysimeter itself – the latter being 0.1 mm – so that the precision of evapotranspiration values calculated from the lysimeter mass balance would not be adversely affected by continuous drainage. Therefore, a load cell range and sensing (datalogging) system precision of at least 0.01 mm was required. Given the 2.25-m$^2$ surface area of the lysimeter, this translated into a weighing precision of 0.0225 kg. An 1112-N (250-lb) load cell (model SM-250, Interface, Inc., Scottsdale, Ariz.) was selected with a 0.0281-mV/V/kg output. A change in mass of 0.0225 kg with this load cell results in a 0.00063-mV/V output change. Thus, a datalogger with at least this resolution was required. Fortunately, the datalogger already in use for sensing the lysimeter scale exceeded this requirement. The drainage system could not be placed inside the lysimeter, either within the soil tank or between the soil tank and the outer enclosure tank. The design could not require major re-plumbing or re-working of the existing lysimeter. The drainage system was required to be out of sight so as not to impede wind movement over the lysimeter, to be near the lysimeter, and to not be subject to freezing. Therefore a buried system within 2 m of the lysimeter was designed. The system was to provide a full-time vacuum of between 90 and 100 cm of water head, automatically controlled. Therefore, cabling for the provision of vacuum measurement, vacuum pump control, and 120-VAC electrical power for the vacuum pump was required. Low cost and ease of installation were requirements leading us to use rigid polyvinyl chloride (PVC) pressure water pipe for the vacuum and drainage storage tanks. There was a tradeoff between depth of excavation, for burying the system, and diameter of pipe versus its cost. It was easy to find a service to auger a hole to any reasonable combination of depth and diameter, so the design was constrained by the cost and availability of PVC pipe. We chose nominal 16-in. (40.6-cm) inner diameter water pipe for the vacuum tank since it was the largest size locally available with end caps, and because we had successfully used it to fabricate the vacuum drainage tanks for our large weighing lysimeters.

## Materials and Methods

The grass lysimeter used in this work is located at Bushland, Texas (35° 11’ N lat.; 102° 06’ W long.; 1,170 m elev. above MSL) where the soil is a Pullman clay loam (fine, mixed, superactive thermic Torrertic Paleustoll). The design of the lysimeter allows no room for installation of a drainage system in the space between the soil tank and the outer enclosure (fig. 1). In the original design, stainless steel tubing was plumbed from the fritted stainless steel filter candles at the bottom of the soil tank up the inside edge of the north wall of the soil tank and terminated at the soil surface with flexible polyvinyl chloride vacuum tubing and connectors for

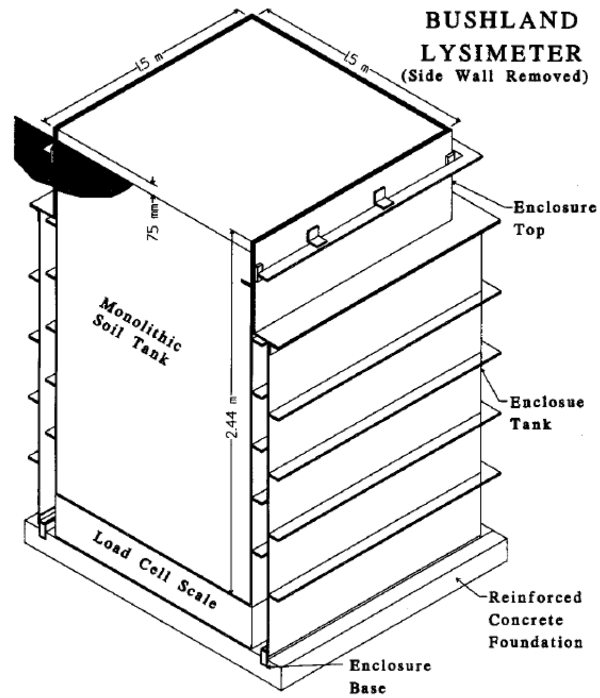


**Figure 1. Isometric view of the low-cost weighing lysimeter at Bushland.**

occasional manual drainage. When not draining the lysimeter, the connectors were terminated with a plug.

The new drainage system connected to the above-ground termination, and included (fig. 2):

- a buried vacuum tank constructed of nominal 16-in. (40.6-cm) diameter rigid polyvinyl chloride (PVC) pipe, closed at the bottom with an end cap and closed at the top with a disc-shaped lid made of 5-cm thick PVC and sealed with a butyl rubber O-ring;
- an inverted U of flexible polyvinyl tubing to bring water from the above-ground termination of the existing drainage system up and over the edge of the lysimeter and below the soil surface outside of the lysimeter for connection to the vacuum tank;
- an inner tank suspended by a load cell from the inside of the lid for collection and weighing of drainage water;
- four ports in the lid for (1) connection of the vacuum line, (2) connection of the drainage tubing from the lysimeter, (3) insertion of a rigid tube for removal of any water that might collect at the bottom of the vacuum tank, and (4) insertion of a rigid tube for removal of water from the drainage collection tank when full; and
- a plastic enclosure (NEMA 12) housing the vacuum pump, ball valves for access to the ports for removal of water, and a pump control unit consisting of a vacuum sensor and relay. Each of the four main system components will be described separately.

All components except the top of the enclosure were buried.

The vacuum tank was a rigid PVC cylinder (38.1-cm inside diameter, 1.27-cm wall thickness, ASTM D224 water pipe), the bottom end of which was closed with an end cap glued with PVC pipe glue. The top end of the cylinder was reinforced by cutting off the top of an end cap and gluing the resulting cylinder to the outside of the PVC cylinder, leaving a double thickness (2.54 cm) of PVC at the top of the

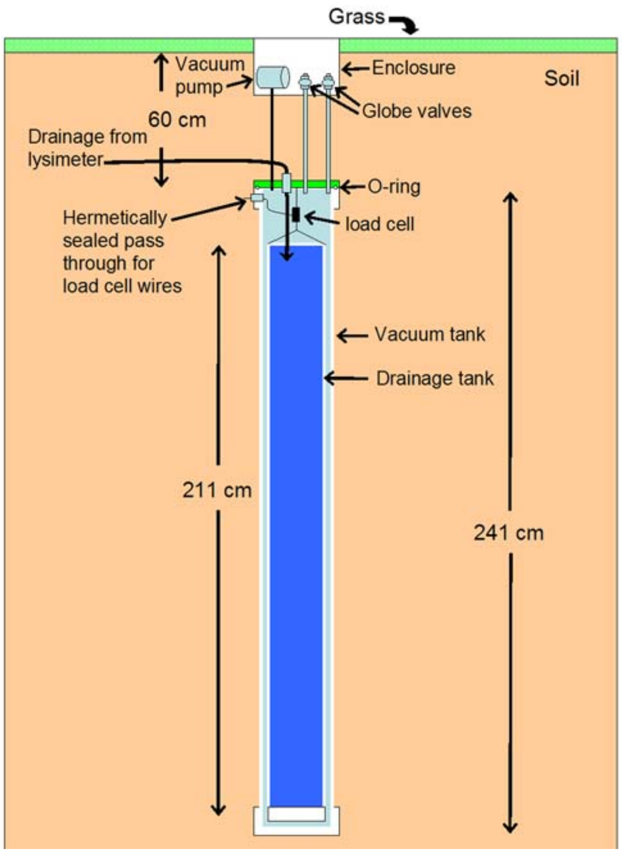


**Figure 2. External vacuum drainage system side-view cross section.**

cylinder. A flat piece of plywood with sandpaper glued to it was used to smooth the cut end and ensure a planar surface against which the lid and O-ring would seal. Fasteners for lid closure were fashioned of 3.2-mm thick aluminum angle, screwed to the outside of the reinforced end of the cylinder with 15.9-mm long stainless steel screws, with nominal 5/16-in. (0.8-cm) diameter stainless steel closure bolts extending upward through the plane of the lid.

The vacuum tank lid was a disc of 5-cm thick rigid PVC with a circular seat for the O-ring seal routed into the bottom side (seat dimensions: 40.64-cm in diameter × 9.5-mm wide × 4.8-mm deep, semi-circular cross section). Holes were drilled in the circumference of the disc for the eight closure bolts that were attached to the vacuum tank. Lowering of the lid over the closure bolts also ensured centering of the O-ring on the top end of the vacuum tank. A stainless steel eye bolt was sealed into a hole in the center of the lid to serve as an attached point for the load cell. Holes were drilled and tapped (NPT) for 1.91-cm (3/4-in.) diameter schedule 80 rigid PVC pipe at 6.35 and 16.51 cm from the center of the lid. The hole closer to the center served for the port for emptying of the drainage tank; and the outer hole served for the port for emptying of any water that might collect at the bottom of the vacuum tank (in case of drainage tank overflow). Legs constructed of 5.08- × 0.32-cm thick aluminum angle were attached to the top of the lid to support the vacuum pump enclosure.

The drainage collection tank was constructed similarly to the vacuum tank, but of 25.4-cm (10-in.) diameter rigid PVC water pipe. An aluminum bracket was screwed to the sides of the reinforced top of the tank to serve as a connection point for the load cell. The load cell was attached to the collection tank and to the lid using stainless steel swivel connectors to relieve any but vertical strains. A six-conductor (AWG 20 stranded) cable was connected to the load cell with twisted and soldered connections insulated with adhesive-lined heat shrink tubing for water resistance. The entrance of the cable was through a 1.27-cm (½-in.) diameter PVC pipe nipple and elbow screwed into a tapped hole in the reinforced side of the vacuum tank. Wires were stripped to bare copper and sealed inside the nipple and elbow assembly with water resistant epoxy resin to prevent vacuum leakage.

The vacuum pump (model MOA-P122-AA, Gast Manufacturing, Inc., Benton Harbor, Mich.) was contained in a NEMA-12 rated polyester resin and fiberglass enclosure through the bottom of which were sealed the pipes for water removal and the vacuum line. The ends of the water removal pipes were closed with ball valves (model 107-454HC, B&K Industries, Inc., Elk Grove Village, Ill.) that could be opened for insertion of 0.64-cm (¼-in.) diameter rigid copper tubing long enough to extend to the bottom of the drainage tank and vacuum tank. Application of suction to this tube allowed removal of water from the vacuum system when full. The enclosure rested on the tops of the aluminum angle legs that extended upward from the lid of the vacuum tank. Also inside the enclosure was a PVC control box containing a grounded electrical outlet (120 VAC), a vacuum sensor, and a fuse-protected relay controlled by a darlington transistor pair connected to a TTL control line from an external datalogger. The datalogger (described later) served to sense the vacuum sensor and to turn on the vacuum pump when vacuum decreased to <3.4-m of water head, and to turn off the pump when vacuum increased to >3.5-m of water head (2.4-m deep lysimeter plus 1.1-m suction head).

## Installation

A motorized 60-cm diameter bucket auger bored a hole to 3.05-m depth, centered at 2.0 m from the north edge of the lysimeter (fig. 3, left). The bottom of the hole was packed and leveled with sand; and the vacuum tank was placed on the sand bed and plumbed to vertical (fig. 3, right). No other foundation was provided since minor settling of the tank was not a concern and tilting of the tank due to soil movement should be minor in this soil. The annular space around the tank was filled with sand to within 20 cm of the top of the tank, which was 61 cm below the soil surface. The sand filling the annular space between tank and soil provides a conduit for drainage of soil water if the soil were to become saturated, further protecting the installation from movement due to freezing/thawing or soil shrink/swell behavior. Experience shows that the tank inner temperature will come into equilibrium with the average soil temperature around the tank; and the tank was placed deeply enough to eliminate any chance of freezing. The load cell was electrically connected to the cable inside the tank using soldered connections protected with thermoplastic adhesive-lined, polyolefin heat-shrinkable tubing. The drainage tank was lowered into the vacuum tank and connected to the load cell, which in turn was hung from the bottom side of the lid. The O-ring was temporarily attached to its seat in the bottom side of the lid using silicone vacuum grease; and the lid was then lowered onto the top of the vacuum tank and fastened in place with nuts over washers (tensioned to partially compress the O-ring) (fig. 4). The aluminum angle legs were screwed to the


**Figure 3. (left) Augering the hole for the drainage system. (right) Plumbing the vacuum tank to vertical.**

**Figure 4. (top) Lowering the lid onto the vacuum tank. The load cell and drainage tank are suspended from the bottom side of the lid. From right to left are the four ports - the pipe providing access for a 0.64-cm (1/4-in.) diameter rigid tube for removing water from the bottom of the vacuum tank, the pipe providing similar access for removing water from the drainage tank, a 0.64-cm (1/4-in.) diameter barbed nipple for connecting the drainage tube from the lysimeter (there is a 15-cm long tube on the bottom side of this ensuring that drainage water falls into the drainage tank), and a 0.64-cm (1/4-in.) diameter barbed nipple for connecting the tube from the vacuum pump. (bottom) Attaching the lid to the vacuum tank with nuts and washers.**

**Figure 5. (top) Platform to support vacuum pump/control enclosure. (bottom) The enclosure in place with the ball valves and vacuum line installed. The remaining penetration is for the electrical and control cables.**

lid; and the pipes and tubing for vacuum and drainage water ingress and removal were plumbed into the top of the lid (fig. 5, top). The vacuum pump enclosure was placed on top of the legs with the pipes passing through the bottom of the enclosure (fig. 5, bottom). Electrical, control, and sensing cables were brought into the enclosure using armored flexible conduit rated for direct burial and appropriate

**Figure 6. (left) The vacuum pump and control enclosure mounted above the drainage tank and with armored flexible conduit in place. The space under and around the enclosure was subsequently filled with soil and sodded. (right) The enclosure showing the vacuum pump in the open control box. Also in the control box is a smaller plastic enclosure holding the circuit board with pressure transducer, relay, fuse, and darlington transistor pair (right).**

fittings (fig. 6, left). The drainage tube from the lysimeter was a 0.64-cm (¼-in.) inside diameter flexible PVC vacuum tube that was brought over the edge of the lysimeter horizontally and above the lysimeter top edge so as to minimize strain on the soil tank. It was then buried at the depth of the vacuum tank top and connected to the vacuum tank.

### Electrical and Electronic

Connections to the datalogger were via stranded copper twisted pair, shielded cable run in 5-cm diameter rigid PVC conduit to a connection hub (NEMA 12 rated enclosure) and then run in flexible armored conduit to the vacuum pump enclosure. The load cell connection employed three pairs of conductors for a six-wire bridge: two wires for excitation, two for sensing, and two for sensing resistance changes in the 30-m long cable in order to provide temperature correction to the load cell output. The vacuum sensor (model PX26-005DV, Omega Engineering, Inc., Stamford, Conn.) was connected to the datalogger using a four-wire bridge (two twisted pair). Temperature correction of the vacuum reading was not a priority since vacuum was expected to cycle over the hysteresis limits programmed into the datalogger. Control of the relay-driving darlington transistor pair was via two twisted pair, one providing a ground and a TTL level signal to the darlington pair, and the other providing 12 VDC and ground to the relay. Grounds of both pairs were tied together at the pump control circuit board (fig. 6, right). Electrical power for the vacuum pump was provided with a three-conductor (common, high, and earth ground) 10 AWG stranded copper cable (type TC THHN or THWN conductors, sunlight resistant, 600V, direct burial, AIW Corp.) run in buried rigid PVC conduit.

The datalogger (model CR7, Campbell Scientific, Inc., Logan, Utah) was programmed to sense the drainage tank load cell and the vacuum sensor at 10-s intervals. The load cell bridge was excited at 1300 mV; and the bridge measurement was made with an input range of 5000 μV. These were adjusted with the drainage tank full of water in order to achieve the smallest input range possible without over ranging, thus achieving the best resolution possible. Load cell readings were converted to mass (kg) using a calibration done after installation (described later) and averaged into mean values over 15-min intervals for storage by the datalogger. The vacuum sensor was calibrated versus water column height on site. The datalogger was programmed to compare the vacuum sensor reading to two limit values every 10 s, and to send the appropriate TTL signal to the pump control circuit. If vacuum decreased to <3.4 m of water head the signal wire was set to +5 VDC, turning on the pump; and if vacuum was >3.5 m of water head the signal wire was set to 0 VDC, turning off the pump. Because the tank held vacuum very well, and to limit heating of the vacuum pump motor, the duty cycle was limited to 5 min in every 30 min by including a loop in the datalogger program.

### Calibration and Testing

Installation was complete in February 2006 and testing occurred over the next months. While still in the shop, the vacuum tank was tested by bolting on the lid and applying 100 kPa of vacuum, then turning off the vacuum line and observing the vacuum reading with a pressure gage. Over 24 h there was no discernible decline in vacuum; and there was no noticeable change in tank wall shape. Testing in the field included a static test with vacuum applied, but with no connection to the lysimeter drainage system, in order to quantify the precision of the weighing system. Proper cycling of the vacuum system was verified by logging the vacuum reading. Calibration was accomplished after installation by filling the tank to capacity with well water, taking 10 1-min mean readings of the load cell with the datalogger, then removing an aliquot of water using a separate bottle and vacuum pump, followed by 10 more 1-min readings, and repeating the removal of water followed by 10 readings until the drainage tank was empty at which time 10 more readings were taken. Each aliquot, which averaged ~8 kg, was weighed using a balance traceable to NIST with a tolerance of 1 g.

Calibration resulted in a root mean squared error of 0.0029 kg ($r^2$ = 0.99999), equivalent to 0.0013 mm for the 2.25-$m^2$ lysimeter. This greatly exceeded the desired specification of at least 0.01 mm and resulted in negligible error in the change-in-storage term of the water balance.

## Discussion and Conclusion

The system initially drained considerable water from the lysimeter; but after two months, drainage rate was less than 1 mm in two weeks (fig. 7). Operation of the lysimeter was

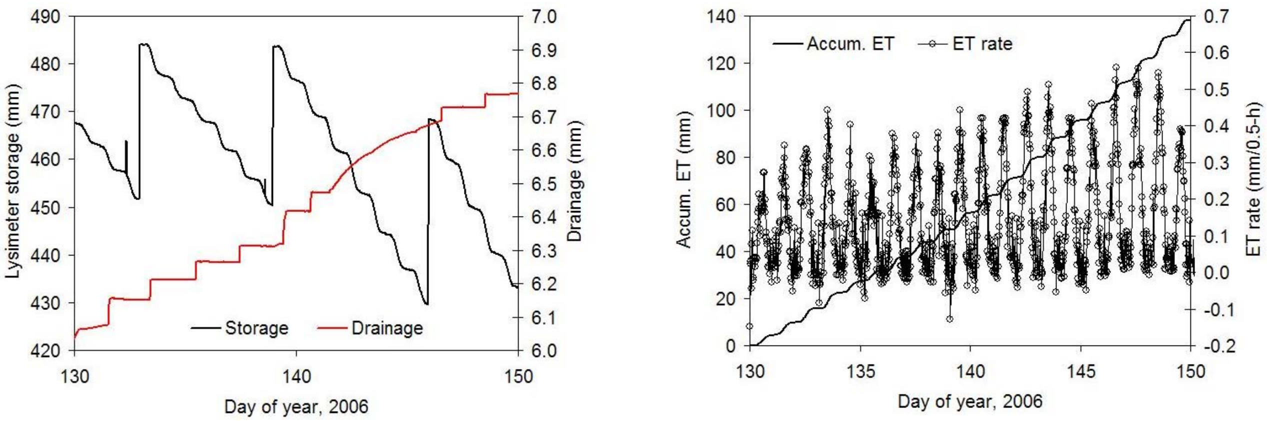


**Figure 7. (left) Example of lysimeter mass (storage) and drainage mass, both converted to equivalent depth of water in mm. Three irrigations are shown, each about 25 mm. Also shown are two spikes in mass caused by an operator standing on the lysimeter to take neutron probe measurements. (right) Accumulative grass ET for the same time period calculated by taking the negative of the lysimeter storage and then adding precipitation and irrigation amounts and subtracting drainage amounts, all in units of mm. Also shown is the ET rate in mm per one-half hour. Although some of the smaller negative ET rate values shown are noise, the larger ones are caused by dew fall.**

routine except that the ET calculations now included subtraction of the amount of water drained from the lysimeter as well as the addition of irrigation and precipitation amounts. Vacuum leaks remained small enough that the pump needed to be turned on only once every half hour to maintain the total suction of 3.45±0.05 m of water head. Drainage was episodic on approximately a 24-h interval, with some periods of more steady drainage as shown after the second irrigation in figure 7 (left). The episodic behavior is unexplained, but may be due to diurnal water viscosity changes in the inverted U tubing that connects the above-ground termination of the existing lysimeter drainage system to the vacuum drainage system; or, it may be due to drainage water slowly rising in the stainless steel tubing inside the lysimeter until water reaches the top of the inverted U at which time it rapidly drains into the storage tank. This behavior is not seen in our large weighing lysimeters (Marek et al., 1988), in which the drainage system is hung from the bottom of the lysimeter and water moves always downward when draining from the lysimeter to the vacuum tanks. Because water drained from the lysimeter is measured on the same time interval as lysimeter mass, the episodic nature of the drainage does not affect the accuracy of ET determinations. Accumulative ET and ET rates calculated from the data show that the lysimeter system is capable of determining ET with high precision, including the capture of some dew-fall events (negative ET rate values in fig. 7, right). The goal of eliminating the saturated soil condition at the bottom of the lysimeter was achieved (fig. 8).

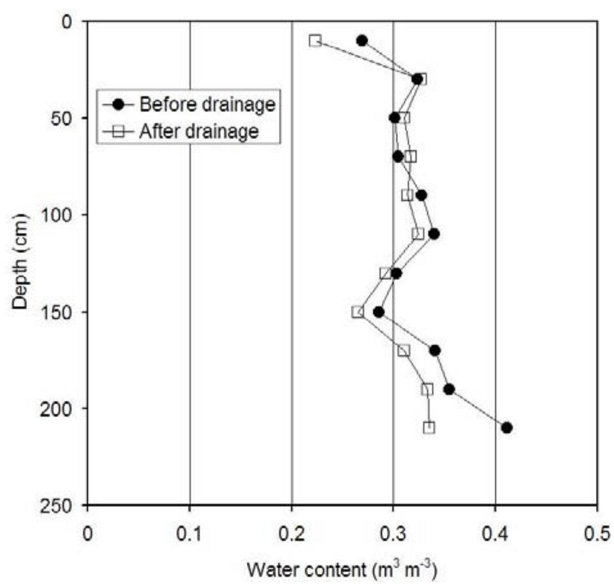


**Figure 8. Profile water contents determined before the automatic vacuum drainage system was installed and two months after installation. Excess water in the lower half of the profile has been removed, reducing water content at the bottom of the lysimeter to field capacity. Saturation in this soil is ~0.42-m$^3$ m$^{-3}$ water content and field capacity is ~0.33 m$^3$ m$^{-3}$. Further reduction in water content is unlikely due to the relatively small suction (~10 kPa) that can be achieved with the drainage filters, which have an air entry value of 10 kPa, and the shallow rooting system of the grass.**

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